Belowground Biogeochemistry Scientific Focus Area

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Developing predictive understanding of belowground biogeochemistry and improving terrestrial ecosystem modeling capabilities

The world's soils and their cycling of carbon and nutrients play a critical role in ecosystem productivity, maintaining atmospheric carbon dioxide (CO_2) concentrations and terrestrial carbon sinks. Carbon cycling involves microbial, plant, and abiotic processes responsible for soil organic matter (SOM) chemistry, transformation, and loss, which are also intimately coupled to nitrogen availability to plants and microbes.

Accurate understanding of these soil biogeochemical processes is critical for predicting ecosystem responses to changes in climate, but current gaps in understanding of soil-plant-microbe interactions make estimates of ecosystem-climate feedbacks highly uncertain. Moreover, subsoils contain twice as much carbon as surface horizons globally, yet their contribution to soil-atmosphere feedbacks has largely been ignored.
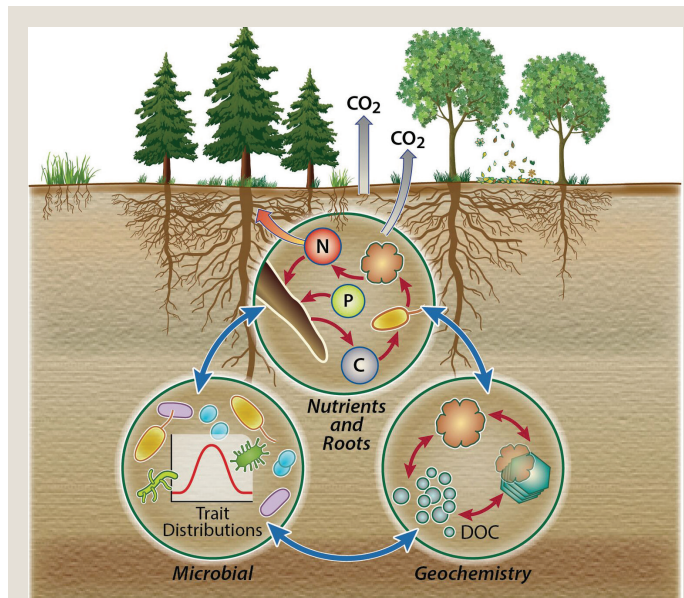
To address these challenges, the Environmental System Science (ESS) program within the Department of Energy's (DOE) Office of Biological and Environmental Research (BER) is supporting the Belowground Biogeochemistry Scientific Focus Area (SFA) led by Lawrence Berkeley National Laboratory.

This SFA aims to develop a predictive understanding of belowground biogeochemistry in the soil-plant-microbe-climate system, with an emphasis on the whole soil profile, and to improve capabilities for modeling terrestrial ecosystems and their role in the climate and Earth systems. To accomplish these goals, this SFA integrates a team of experts in biogeochemistry and ecosystem ecology, microbial ecology and genomics, geochemistry, and ecosystem modeling.

Belowground Cycles. *Illustration of the plant-soil-microbe system. Key: CO_2, carbon dioxide; N, nitrogen; P, phosphorus; C, carbon; DOC, dissolved organic carbon.*

Key Science Questions

The overarching challenge driving the Belowground Biogeochemistry SFA is developing predictive understanding of the role of soils in terrestrial feedbacks to atmospheric and climate changes over the next 100 years. Specific science questions to address this challenge include:

- How do vertical variations in soil microclimate, roots, plant inputs, microbial physiology and community dynamics, minerals, soil organic matter (SOM) properties, and abiotic processes influence SOM cycling over depth?
- How do the interactions among the processes and properties in the first question influence the response of SOM cycling to environmental changes over time?
- How does the emergent response to changing conditions manifest across different spatial and temporal scales for soil carbon cycling and coupled plant-soil-microbial biogeochemistry?
- What is the potential for whole-profile soil organic carbon loss and change in ecosystem-carbon balance due to environmental changes over the 21st century?
- What is the best way to represent a generalized set of principles governing soil carbon dynamics and nutrient cycling to improve ecosystem models for Earth system analysis?

A critical part of the integrated model-experiment research is developing robust, generalizable tools for understanding and predicting soil biogeochemical responses to global change across spatial and temporal scales. This research will also inform other fundamental and DOE-mission relevant questions regarding the future role of soils in bioenergy, nutrient provision, and the water cycle.

Research Approach

Scientists are employing a coordinated set of field and laboratory experiments, combined with advanced analytical techniques and process-rich modeling, to characterize the controls on organic matter cycling and soil-plant-microbe-nutrient interactions and how they shape ecosystem responses to climate change. Designed in coordination with modeling, experimental results are relevant to model development and can address the challenges of spatial and temporal scaling. Research focuses on the whole-soil profile, and a novel, whole-soil warming experiment serves as an integrating platform to study belowground biotic and abiotic processes governing biogeochemical cycles.

Research Tasks and Recent Results

SFA research is organized into four main tasks: (1) biogeochemistry and whole-soil warming, (2) microbial responses and feedbacks, (3) geochemical controls on SOM de/stabilization, and (4) soil biogeochemistry and carbon cycle modeling.

Blodgett Forest Whole-Soil Warming (Left). *In the central experiment of the Belowground Biogeochemistry SFA, the whole profile of a forest soil is warmed by 4ºC year round to look at plant inputs and decomposition pathways, microbial processes, and long-term stabilization.* **(Right)** *Scientists measure the effect of warming on carbon losses and microbial activity.*

Model Integration

The Belowground Biogeochemistry SFA employs process-rich, fine-scale models, as well as simpler representations for global applications. This approach enables the exploration of mechanisms at the scale of observations and the extraction of parsimonious process representation for integration into DOE's Energy Exascale Earth System Model (E3SM) Land Model (ELM). The long-term vision is a modeling capability that can be applied across temporal and spatial scales, providing insights into experimental results such as soil response to warming and other manipulations and the vulnerability of old SOM to perturbations. Future research will focus on testing the models across a wide range of soil types, chemistries, plant inputs, climate regimes, and manipulations.

Task 1 built and maintains long-term, whole-soil warming experiments in the field and measures emergent ecosystem responses to warming, such as soil CO_2 respiration and nutrient availability. Results are showing that soil temperature has a large effect on decomposition, at all depths. Warming by 4°C increased decomposition at all soil depths by about 35%, a temperature sensitivity of respiration higher than what is predicted by current Earth system models.

Task 2 determines how microbial traits, physiology, and community properties vary throughout the soil profile and in response to environmental changes, and investigates how they affect SOM

mineralization rates, pathways, and products. SFA research indicates that microbial carbon use efficiency (CUE) has a nonlinear response to warming consistent with microbial community reassembly. CUE, determined based on novel stable isotope-based techniques, showed an unexpected increase with warming, which was associated with enrichment of organisms with slower growth strategies and intrinsically higher CUE.

Task 3 examines how SOM chemical composition and the interactions of organic molecules with minerals and metals influence SOM availability to soil microbial transformations or leaching. In recent results, mineral stabilization explains long-term persistence of highly labile substrates. Decomposition of labile substrates was effectively stopped when they were sorbed to mineral surfaces.

Task 4 improves modeling of key processes for decomposition, including microbial activity, nutrient limitations, and the effects of moisture and temperature on organomineral interactions. The new soil process representations are being incorporated into DOE's ELM and are important for benchmarking model performance after perturbations. Model predictions are improved by representing mineral, microbial, and transport processes. By including key missing processes such as sorption-desorption in a soil carbon model, SFA researchers produced the first simulation reproducing observed ^{14}C profiles and old carbon at depth.
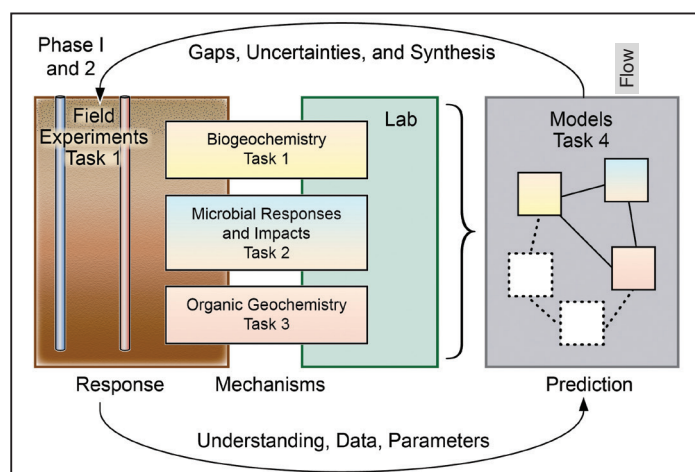
SFA Research Organization. *The Belowground Biogeochemistry SFA is organized into four main tasks with field and laboratory experiments tightly coupled with modeling to enable predictive understanding of belowground processes governing biogeochemical cycles.*

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